1. RADIOACTIVITY and RADIATION PROTECTION

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1.1. Definitions

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

- **Unit of activity** = becquerel (curie):
  1 Bq = 1 disintegration s^{-1} [= $1/(3.7 \times 10^{10})$ Ci]
- **Unit of absorbed dose in any material** = gray (rad):
  1 Gy = 1 joule kg^{-1} (= 10^4 erg g^{-1} = 100 rad)
     = 6.24×10^{12} MeV kg^{-1} deposited energy
- **Unit of exposure**, A measure of photon fluence at a certain point in space integrated over time, in terms of ion charge of either sign produced by secondary electrons in a small volume of air about the point:
  = 1 C kg^{-1} of air (roentgen; 1 R = 1 esu cm^{-3} in air = 2.58×10^{-4} C kg^{-1})
  Implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving (so-called charged particle equilibrium). This unit is somewhat historical, but appears on many measuring instruments.
- **Unit of equivalent dose** (for biological damage) = sievert [= 100 rem (**r**oentgen **e**quivalent for **m**an)]: Equivalent dose H_T (Sv) in an organ T is equal to the absorbed dose in the organ (Gy) times the radiation weighting factor w_R (formerly the quality factor Q, but w_R is defined for the radiation incident on the body). It expresses long-term risks (primarily cancer and leukemia) from low-level chronic exposure. It depends upon the type of radiation and other factors, as follows [1]:

Table 1.1: Radiation weighting factors.

Radiation	w_R
X- and γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
10–100 keV	10
> 100 keV to 2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons (other than recoils) > 2 MeV	5
Alphas, fission fragments, & heavy nuclei	20

The sum of the equivalent doses, weighted by the tissue weighting factors w_T of several organs and tissues of the body that are considered

to be most sensitive [1], is called "effective dose" E:

$$E = \sum_T w_T \times H_T \qquad (1.1)$$

1.2. Radiation levels [2]

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate $\approx$ (0.4–4) mSv (40–400 mrem). Can range up to 50 mSv (5 rem) in certain areas. U.S. average $\approx$ 3.6 mSv, including $\approx$ 2 mSv ($\approx$ 200 mrem) from inhaled natural radioactivity, mostly radon and radon daughters (Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines. 0.1–0.2 mSv in open areas).

• **Cosmic ray background** in counters (sea level, mostly muons): ~ 1 min^{-1} cm^{-2} sr^{-1}. For more accurate estimates and details, see the Cosmic Rays section (Sec. 24 of this *Review*).

• **Fluence** (per cm^2) to deposit one Gy, assuming uniform irradiation:
$\approx$ (**charged particles**) $6.24 \times 10^9/(dE/dx)$, where dE/dx (MeV g^{-1} cm^2), the energy loss per unit length, may be obtained from Figs. 27.3 and 27.4 in Sec. 27 of this *Review*, and pdg.lbl.gov/AtomicNuclearProperties.
$\approx 3.5 \times 10^9$ cm^{-2} minimum-ionizing singly-charged particles in carbon.
$\approx$ (**photons**) $6.24 \times 10^9/[Ef/\ell]$, for photons of energy E (MeV), attenuation length ℓ (g cm^{-2}), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \ell$ but large enough to contain the secondary electrons.
$\approx 2 \times 10^{11}$ photons cm^{-2} for 1 MeV photons on carbon ($f \approx 1/2$).

• **Recommended limits to exposure of radiation workers (whole-body dose):**[*]
EU/Switzerland: 20 mSv yr^{-1}
U.S.: 50 mSv yr^{-1} (5 rem yr^{-1})[†]

• **Lethal dose**: The whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) is 2.5–4.5 Gy (250–450 rad), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

• **Cancer induction by low LET radiation**: The cancer induction probability is about 5% per Sv on average for the entire population. [1]

Footnotes:

[*] The ICRP recommendation [1] is 20 mSv yr^{-1} averaged over 5 years, with the dose in any one year $\leq$ 50 mSv.

[†] Many laboratories in the U.S. and elsewhere set lower limits. See full *Review* for references and further details.